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Sustainability guardrails for energy scenarios of the global energy transition

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ABSTRACT

Sustainability guardrails in global energy scenarios were reviewed and further developed based on a literature review of global energy system transition scenarios. Environmental planetary boundaries mark out the safe operation space for human activities. The planetary boundary framework has yet to be fully incorporated into global energy scenario modeling, where the emphasis has been almost solely on CO_2 emission mitigation. Stress on biochemical flows, land use change, biodiversity, ocean and climate systems are often neglected. Concurrently, social and economic aspects, such as limiting air pollution, providing universal access to modern energy services and improving energy efficiency by electrification of energy services are emerging as new paradigms in energy scenario modeling frameworks. However, ethical choices, such as current and future generations' access to preserved ecosystems, aversion of energy resource risks, preventing resource use conflicts, and negative impacts on human lives from energy extraction and use are not usually discussed or justified in energy scenario modeling. All investigated global energy transition scenarios failed to adequately describing the critical roles of flexibility in future energy systems based on high shares of renewable energy, such as storage, grids, demand response, supply side management and sector coupling. Nor did they adequately incorporate the concept of resilience in socio-ecological systems.

1. Introduction

It has been recognized that human civilization is over-exploiting planetary resources faster than they are being renewed [1]. Nine planetary boundaries have been defined to assess the safe limits into which human activities should be confined in order to take into account assimilative capacities of the planet, related uncertainties, the complexity of the biosphere, and possible tipping points [2,3]. Currently, the biosphere's capacity to assimilate the impacts of human action is being exceeded, resulting in dangerous interference in the global climate system [4], an increased rate of biodiversity loss, and overstressed nitrogen and phosphorus cycles [2,3]. In addition, the planetary boundaries framework includes stratospheric ozone depletion, ocean acidification, chemical pollution, land-system change, freshwater use and aerosol loading [2]. Human activities are the largest drivers at the planetary scale, thus the current geological era has been proposed to be named the "Anthropocene" [5]. The growing awareness of the environmental state of the planet and concerns about the threats of climate change have led world leaders to agree on a shared, long-term goal of limiting global emissions of greenhouse gases to ensure a 2 °C compatible pathway within this century, and pursue efforts to limit global warming to 1.5 °C above pre-industrial levels [6]. A common, long-term, legally binding climate target is a start; however, a truly sustainable development of resource extraction and use for human needs would address the other planetary boundaries as well.

Motivations of influential global energy scenarios differ. Governments can assess implications of different energy and environmental policies, non-governmental organizations (NGOs) can draw attention to alternative polices, and companies can assess market risks and their investments [7]. Thus, an energy scenario can be handcrafted to drive certain interests. For this reason, transparency in the creation of energy scenarios is essential, since model assumptions greatly affect

Abbreviations: 2DS, Two degree scenario; AFOLU, Agriculture, forestry and land use; BECCS, Bioenergy and carbon capture and storage; BEV, Battery electric vehicle; CAES, Compressed air energy storage; CCS, Carbon capture and storage; CCU, Carbon capture and utilisation; COP21, Twenty first annual Conference of Parties; CSP, Concentrating solar thermal power; DACCS, Direct air carbon capture and storage; EMF, Energy Modeling Forum; ETP, Energy Technology Perspectives; hi-Ren, High renewable energy; hi-Nuc, High nuclear energy; GEA, Global Energy Assessment; GHG, Greenhouse gas; IAM, Integrated assessment modeling; IEA, International Energy Agency; IIASA, International Institute for Applied Systems Analysis; IMF, International Monetary Fund; IPCC, Intergovernmental Panel on Climate Change; IRENA, International Renewable Energy Agency; LCOE, Levelised cost of electricity; NELD, Non-economic loss and damage; NGOs, Non-governmental organizations; OECD, Organization for Economic Co-operation and Development; PHS, Pumped hydro storage; ppm, Parts per million; PtX, Power-to-X; PV, Photovoltaic; R&D, Research and development; RE, Renewable energy; TES, Thermal energy storage; WBGU, German Advisory Council on Global Change; WEC, World Energy Council; WEO, World Energy Outlook; WRI, World Resource Institute; WWF, World Wildlife Fund; WWS, Wind, wave and solar; Subscripts, eq, Equivalent

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the modeling outcomes. For example, incorrect assumptions have often been made concerning the future costs of solar photovoltaics (PV), no doubt a key technology on global level. In one case, Luderer et al. claim capital costs for solar PV projects will be in the range of 800–1400 $/kWp (620–1080 €/kWp[1]) in 2050. In reality, utility-scale project costs in Europe, India and China have already reached those same price levels today [8,9], and PV experts expect costs in the range of 360–520 €/kWp [10] and 320–430 €/kWp [11] in 2050, depending on the deployment scenario. Transparency of assumptions thus becomes an important precursor to assessing the quality of a scenario.

It appears safe to assume that a global energy transition is underway, and that world leaders will need to provide plans and solid policy options for the future. To do this, realistic and valid information concerning key technologies that drive the transition must be presented. It appears clear that global installed capacity of solar PV will increase significantly and that the cost of this technology will fall accordingly. The same could be argued for wind power. Therefore, policymakers must be able to carefully consider the important nature of solar PV and wind power technology costs relative to future global, cumulative installed capacities. In addition, such weather dependent energy generation technologies must be seen in the context of greater temporal and spatial accuracy, something which is neglected in past IAM exercises. Such consideration can only arise from accurate and relevant energy system model frameworks that conform to a meaningful set of sustainability criteria. Several studies which do have high temporal and spatial resolution on a continental scale and realistic technological representation of weather dependent power generation imply that fully renewable energy mixes, mostly based on wind and solar PV, are technically and economically viable options [12–14]. First insights from global scale modeling with an hourly resolution for a full year imply that not only are fully renewable power systems technically possible, they are economically attractive as well, from the system point of view and all over the world [14–17].

The ongoing energy transition is not only technological, but also a combination of economic, political, institutional and socio-cultural changes; thus, it should be guided by ethics and sustainability [18], as well as with a resilience perspective [19]. Importantly, the mitigation of climate change must not only be seen as a challenge to be overcome, but as a real-life, real-time struggle to prevent damage to humans, many of whom are paying or will pay disproportionate costs related to climate change. These groups include people who may be most vulnerable to the impacts of climate change, such as future generations, minority groups, and people in economically disadvantaged countries. Determining energy mixes for energy scenarios requires ethical choices due to long reaching impacts of energy decision-making and profound impacts on economics, the environment and people's lives. Consequently, future energy scenarios take on the role of long-term social contracts, which must be based on principles of justice [20].

For these reasons, the first aim of this study is to highlight the need for consideration of planetary boundaries and other sustainability principles in global energy scenario frameworks. This consideration includes not only climate change constraints, but other limitations as well. Second, we propose a literature derived hierarchy and sustainability guardrails according to which future global energy scenarios (and the transition) could be scrutinized. Third, we investigate whether sustainability guardrails have been deployed before in global energy scenarios and discuss how the determined sustainability principles could be operationalized into the creation of energy scenarios. This includes what kind of indices can be used for tracking the sustainable development of the global energy system.

2. Sustainability guardrails for the global energy system

Generally, sustainable futures must acknowledge that certain levels of cost and damage are intolerable, no matter what short term gains can be achieved. To this one can add that certain rights are inalienable. In essence, higher normative requirements will always outweigh any gains that can be achieved through intolerable acts. Such is the motivation for opposing such things as slavery, inequality, child labour, hazardous work conditions, etc. And this same motivation can be extended into all three spheres of sustainability (social, environmental, economic). Specifically, the world can seek to exclude anything which is unacceptable by establishing clear boundaries of tolerance. Such boundaries have also been introduced as guardrails for sustainable energy policy [21]. The German Advisory Council on Global Change (WBGU) has applied the principle of setting normative guardrails in order to create a sustainable global energy scenario. WBGU's ecological guardrails consist of compliance with a climate protection window, protection of marine ecosystems (by limiting carbon sequestration), sustainable land use (by limiting bioenergy), protection of rivers and catchment areas (by limiting large hydro power) and prevention of air pollution. The socio-economic guardrails include keeping risks within a normal range (by limiting nuclear power), preventing disease caused by energy use, limiting the proportion of income expended on energy, providing access to modern energy services, meeting an individual minimum requirement for modern energy services, and establishing a minimum level of macroeconomic development. Similarly, according to a definition by the Brundtland Commission [22], we should ensure that future generations are able to meet their needs, and that the resource limitations for sustainable development are contemporary and bounded by the present state of technology, social organization around environmental resources, and the ability of the biosphere to absorb human activities.

Häyhä et al. [23] point out that although the planetary boundaries framework proposes quantitative global limits, decisions regarding resource use and emissions are made nationally and sub-nationally. Thus, the operationalization of planetary boundaries as biophysical, socio-economic, and ethical dimensions in national policymaking is of high priority. Keeping this in mind, the realization of multiple sustainability targets requires that they can be simplified to pass in real world politics, as is argued to be the case for the two degree target. Determining sustainability targets in an objective manner is no easy task given that some guardrails must never be breached. For this reason, Serdeczny et al. [24] propose a framework for categorising different aspects of non-economic loss and damage (NELD): human life, meaningful places, cultural artefacts, biodiversity, communal sites, intrinsic values, agency (the ability to engage with or change one's world), identity, production sites and ecosystem services. The identified methods for valuing NELD are economic evaluation, multi-criteria decision analysis, composite risk indices, and qualitative and semi-quantitative approaches.

Given that social and economic sustainability targets are context dependent and subjective choices, their valuation could be based on the United Nation's development goals [25], global question polls, and participatory workshops. For example, 10 000 citizens from 76 countries participated in a global survey [26], and the majority of respondents (56%) preferred subsidization for wind, solar, marine and geothermal energy resources in order to make large scale cuts in greenhouse gas emissions. A very high proportion (97%) of the participants thought that a global dialogue, such as the survey they answered, should be conducted in the future when dealing with similar issues.

It can be argued that sustainability principles are hierarchical (Fig. 1). In the concept of strong sustainability, it is emphasized that certain elements of natural capital[2] are irreplaceable [27], and thus the

[1] A long-term exchange rate of 1.3 USD/EUR is applied in this study. Brackets signal conversion preceded by original number.

[2] Consists of resources for production, waste absorption from production, life-support

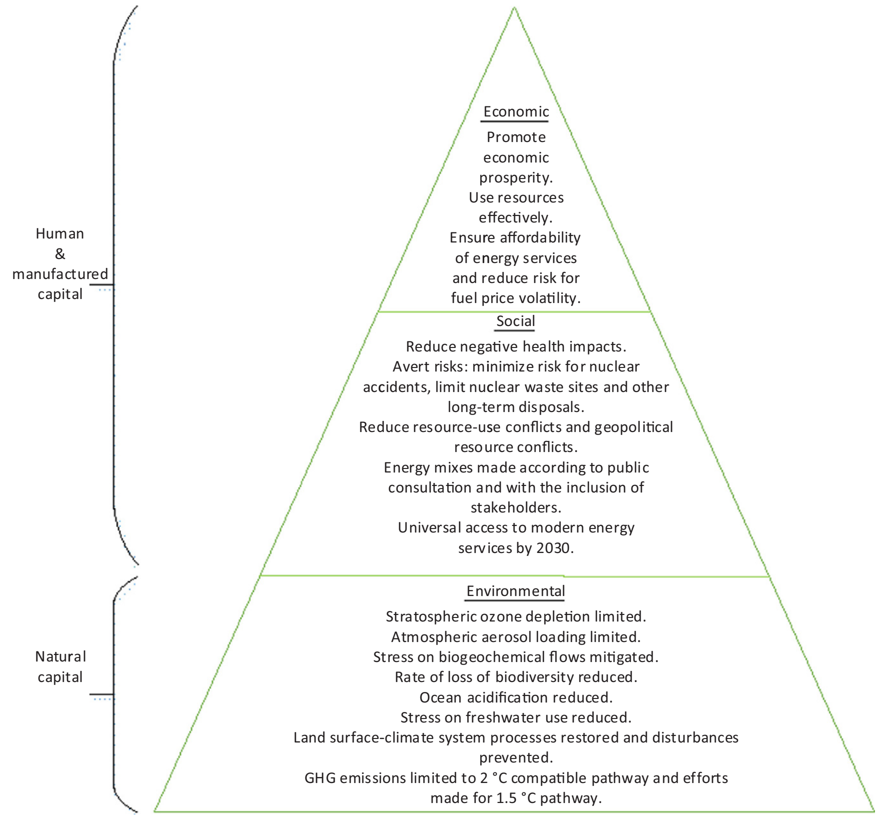

Fig. 1. Proposed hierarchical framework for assessing sustainability of global energy scenarios.

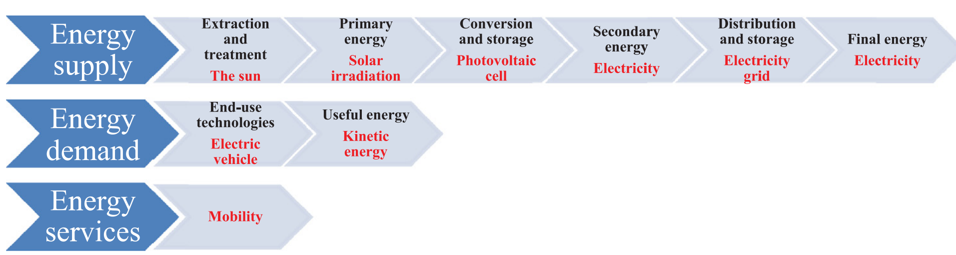

Fig. 2. Simplified representation of an energy system, with an example (in red) of the many stages a resource will pass through before becoming an energy service. Adapted from [29].

use of natural capital should not lead to irreversible destruction of this capital [28]. It follows that the human use of natural capital should be limited in such a way that it is not depleted. Given that there are ecological limits, or tipping points with points of no return, it can be thought that dimensions of sustainability have a hierarchy; and the environmental dimension serves as the basis for other sustainability dimensions. Thus, the planetary boundaries framework sets the foundation for sustainable energy systems.

Fig. 2 highlights how sustainability goals can be achieved throughout the complicated, multi-stage process that defines an energy system. Such a system begins with energy resources that go through technological conversion into useful forms of energy and possible storage. These forms of energy are then used to satisfy demands for energy services.

Difficulties in taking sustainability criteria into account when assessing energy scenarios arise from the fact that an energy system involves a multi-stage process of satisfying demands for energy services (Fig. 2). In addition, sustainability criteria can be applied to either one or more of these stages. In general, the energy system can be divided into a supply side and a demand side. On the supply side, there are upstream aspects to consider, such as the extraction and treatment of a resources so that a form of primary energy is produced. Downstream aspects include conversion, distribution and storage technologies that ultimately give rise to a form of final energy that can be supplied to end-users. On the demand side, end-users employ technologies to create a useful form of energy that provides a desired energy service. Sometimes this process is simple, such as a person moving in and out of the sun or shade to keep warm or cool. In most cases, however, the process can be quite complicated. A detailed representation of this process is found in [29].

2.1. Operationalising sustainability guardrails

Operationalising a sustainability criteria into energy scenario creation, therefore, involves judging how and where the criteria impacts the process. For example, using a resource efficiently not only implies examining efficiency of end-use technologies, but also includes potential improvements downstream and upstream in the supply chain. Further, one could question whether a demand itself is reasonable in relation to a different demand in another part of the world. Likewise, promoting

(*footnote continued*)
functions and amenity services [27].

universal access to modern energy services may not merely involve such elements as improving the quality of resource distribution (e.g. electricity transmission grid extension), but a sustainable solution could be found from another aspect of the energy system (e.g. an off-grid solar PV system). For these reasons there may indeed be more than one potential pathway towards sustainability. In the case of the current energy transition, several potential solutions have risen to the fore: efficiency, renewable energy (primarily solar, wind and biomass), nuclear energy, carbon capture and storage, and energy subsidies. Therefore, the hierarchical nature of the sustainability criteria presented in Fig. 1 may aid in resolving differences in opinion or expose/eliminate vested interests in scenario design.

2.1.1. *Efficiency*

Efficiency can be achieved in several ways. A common suggestion is that electrification of energy services, where applicable, is a key for reducing primary energy use. For example, a battery electric vehicle (BEV) powered by wind or solar energy is about 3 and 4 times more efficient than diesel and petrol based vehicles, respectively, as measured by well-to-wheel fuel consumption in litres of gasoline equivalent per 100 km driven [30]. Further, electric heat pumps are about 4.5–5.5 times more efficient than direct heating from combustion, and modern cooking technologies are 2–3 times more efficient than traditional appliances [31]. Efficiency gains can also occur from changes to the built environment through adopting new standards for new buildings and increasing renovation rates of existing buildings.

However, energy scenarios may fall short of reaching fully sustainable targets for energy efficiency. The seventh UN Sustainable Development Goal sets out targets for energy, including those specific to efficiency. A recent UN report [32] observes that over the period of 1990–2010, global energy intensity (or the amount of energy needed produce a unit of GDP) fell 1.3% annually, from 10.2 to 7.9 MJ/USD_{2005}. Moreover, the UN target is to double the rate of energy efficiency improvement, to 2.6%/year by 2030. In a recent IEA analysis of the Nordic countries [33], achieving the 2 °C requirement would require a building renovation rate of about 2–3%/year, well beyond current rate of 0.5%/year achieved in the Nordic countries. In other words, striving for a 1.5 °C target would require even more stringent renovations rates. Such stringent targets may indeed aid in reaching one sustainability target (efficiency), but could result in other sustainability issues, such as a potentially unrealistic target being set without proper public consultation and inclusion of stakeholders, who would ultimately be the drivers of such renovations. In other words, the IEA scenario should have also included comment on how this important aspect of social sustainability was safeguarded. Without such comment, controversy could result. A scenario designed with adherence to a full range of sustainability guardrails could prevent such controversy.

2.1.2. *Renewable energy*

Next, expanded use of renewable energy, particularly solar, wind and biomass, has emerged as a candidate for reaching sustainability goals. According to the International Renewable Energy Agency (IRENA) REmap scenario, renewable energy can constitute 25% of used primary energy in 2030, and combined with efficiency measures in energy consumption, the renewable share in the same scenario can reach 30% of primary energy [31]. Further, some studies suggest that benefits from renewables can extend beyond what is usually perceived as the energy sector. Caldera et al. [34] demonstrate that renewables can alleviate water stress in a financially competitive and sustainable manner around the world. Similarly, the World Resource Institute (WRI) determined thermal generators can worsen water stress in areas that are already freshwater-constrained [35] due to such plants' own demands for water. As a result, solar PV and wind power were viewed as more suitable technologies for providing electricity in such areas, while the authors remind that improving energy efficiency is still the least-cost solution. This is in addition to the fact that solar PV and wind power result in lower GHG emissions.

Biomass as a source of renewable energy generation must be regarded carefully in future energy system scenario design by the application of acceptable sustainability criteria concerning use. Sustainable bioenergy does not cause negative impacts on natural ecosystems, soil fertility, water resources, livelihoods, people's access to food and biodiversity [36]. In 2010, the UN conference of parties agreed to bring the rate of loss of natural habitats close to zero, set a conservation target of 17% for terrestrial and inland water areas and 10% for marine and coastal areas, and aimed to restore 15% of degraded areas through conservation and preservation [37]. In the EU, it seems unlikely that the 2020 biodiversity targets will be met, thus more stringent actions are needed [38]. In the IPCC emission reduction pathways [4], in which CCS is not deployed, the emission estimations for agriculture, forestry and land use change (AFOLU) range from net zero to a possible carbon sink on the level of -15 $GtCO_{2eq}$/a in 2050. Given that in COP21, a pledge was made to pursue efforts to limit the temperature increase to 1.5 °C, the possibility of AFOLU sectors becoming a natural sink for carbon should be enhanced (and better investigated in energy scenarios). A median negative emission level of -5 $GtCO_{2eq}$/a by 2100 is required to limit warming to less than 1.5 °C within the 21st century with more than a 50% probability [39]. Even considering that building, industry, transport and electricity sectors are fully carbon-neutralized, the IPCC puts non-CO_2 emissions at 3–12 $GtCO_{2eq}$/a, highlighting the ambition and challenge of the 1.5 °C target. Avoiding large upfront carbon debt from biomass feedstocks converted to energy must therefore be of high priority. The implication for the creation of energy scenarios, considering strict sustainability criteria, is that the global bioenergy potential in 2050 has been identified at around 80–100 EJ/a of primary energy [21,29,36,40].

2.1.3. *Nuclear power*

The overall sustainability of nuclear power was recently discussed in the context of the Finnish energy system [41]. Several sustainability issues related to nuclear power were also discussed that were global in nature. First, there are environmental concerns regarding decommissioning of nuclear power plants and the disposal of nuclear waste. In many parts of the world, such as Finland, sites of nuclear plants are not expected to be recovered back to their original state, and become permanently affected by previous operations. This, along with the long lifetime of nuclear waste, represents an inter-generational ethical dilemma of whether current society has the right to impact the environment over such a long time scale. Second, Leuraud et al. [42] showed a link between protracted low-dose radiation exposure and an increased risk of leukaemia in nuclear power plant workers. Third, Sovacool et al. estimate that a collective 686 global nuclear safety incidents from 1950 to 2014, including large-scale events such as those witnessed in Fukushima and Chernobyl, have resulted in approximately USD 265 billion in property damage and 182,794 deaths. These larger-scale events also have irreparable impacts on ecosystems due to genetic mutations in flora and fauna [43], and also spread impacts over greater distances [44,45]. Moreover, it is estimated that disasters similar in magnitude to Fukushima have a 50% probability of occurrence every 60–150 years [46]. In addition, while the frequency of such events appears to be decreasing, their overall severity has increased. These serious risks to environment and health can be seen in addition to global risks associated with nuclear weapons proliferation and the potential of terrorist attacks on nuclear facilities.

It may be argued that there is an unfairness to nuclear power as a global solution for climate change mitigation due to the fact that it is not a conversion technology that promotes equity among nations. Importantly, smaller and less developed nations may find the high initial capital costs prohibitive. In addition, some nations that may aspire to have nuclear power development may have the technology denied to them due to international sanctions. In the recent case of Iran, nuclear power development was obstructed for a decade by UN sanctions,

despite the country's consistent pledges that such development was for peaceful purposes. In the decade of dispute, international tensions were often high, and military posturing was prevalent, which lead to destabilisation throughout the Middle East. Furthermore, some countries may feel unsolicited pressure from neighbouring countries that opt to accept the risks associated with nuclear power. An uneven playing field may develop between international industries that either do or do not have access to highly subisdised nuclear power. More importantly, fallout from nuclear disasters does not honour national borders, leading to further possibilities of dispute. Such unfairness is not seen with renewable energy resources such as the sun and wind. While the quantity of these resources is certainly not uniform globally, there are very few regions on the planet where at least one of these resources is not plentiful. In addition, the conversion technologies are freely shared internationally. Indeed, the growth of global installed capacities of solar PV and wind turbines has lead to significant cost reduction that will continue well into the future, to the mutual benefit of all.

2.1.4. Carbon capture and storage

CCS technology is advocated as a techno-economic mandatory element of a 2 °C scenario in several studies [4,47,48]. However, this claim is questionable given the outdated cost assumptions for renewable energy in the mentioned references, in particular solar PV and supporting battery technology. CCS could be used in reducing industrial sector emissions and eradicating emissions from bioenergy combustion [49]. At the same time, the energy system should be electrified as far as possible to reduce environmental, economic and social burdens. The remaining energy services which cannot be provided through electrification, services for providing seasonal storage, or processes which require a hydrocarbon feedstock, could be substituted with renewable based synthetic hydrocarbons [50] in a carbon capture and utilisation (CCU) process. When the atmosphere is the source of carbon, no large scale CO_2 storage capacities are needed, making the Power-to-X (PtX) concept climate neutral, and removing fuel extraction impacts on the environment. In the end, the entailed uncertainties surrounding fossil CCS in the remaining carbon budget in limiting global warming are large. However, risks are much smaller in a pathway which includes a phase out of fossil fuels starting immediately together with the scale-up of renewable power, compared to a pathway with the continued burning of fossil fuels and advocated large scale CCS deployment scale-up within this century. Indeed, so-called ‘negative emissions’ schemes have recently been challenged [51] as a method of respecting the 2 °C guardrail. Instead, bioenergy with CCS (BECCS) and direct air CCS (DACCS) have been advocated with the important proviso that sustainable sequestration schemes can be deployed. For example, Kriegler et al. point out there is a need for about 10 Gt of CO_{2eq} removal in the 2050 s to achieve the 1.5–2 °C pathways, and BECCS would be a suitable method [52].

There are several more reasons to question the sustainability of CCS. Importantly, costs of carbon capture and storage (CCS) technologies are high compared to alternatives [53]. One of the flagship US CCS plants is years behind schedule, billions of dollars over-budget, and may never turn a profit [54]. Next, the main restrictions for CCS are that the technology is not currently applied beyond a demonstration level in the power sector, potential storage capacities are limited both globally and regionally, relatively small leakage rates can compromise the climate stabilization function, there are remaining emissions from fossil fuel extraction, and there are no ancillary benefits [29]. Finally, recent research findings [55] raise hopes that where substantial quantities of water and porous basaltic rocks are available, CO_2 (for example released from geothermal sites in Iceland) could be safely stored in basaltic rocks. However, considering the remaining constraints of the technology, wide range deployment of fossil CCS in the power sector is not part of a sustainable energy system.

2.1.5. Direct and indirect subsidies

It is difficult to compare the economics of energy technologies on a vis-á-vis basis as subsidies cloud the issue. According to IEA definitions, fossil-fuel and renewable energy subsidies were 493 and 135 bUSD (380 and 104 b€) in 2014, respectively [56]. These same subsidies for fossil fuels result in premature deaths through local air pollution, exacerbate congestion of vehicles and increase atmospheric greenhouse gas concentrations [57]. Taking this into account, the International Monetary Fund (IMF) reports that the subsidies for coal alone cost 3.9% of global GDP, while total fossil fuel subsidies amounted to 6.5% of global GDP, or 5302 bUSD (4078 b€), in 2015 [57]. In addition, it is often neglected that as major economies rely on imported energy, part of their military expenditures can be accounted for in securing overseas supplies of energy, adding to the energy bill of fossil fuels. An estimate puts the annual military costs for the US securing Persian Gulf oil supplies at 219 bUSD for 1976–2007 [58]. Delucchi and Murphy [59] estimate the opportunity cost and conclude that, were there no oil in the Persian Gulf, then US combined wartime and peacetime defense expenditures might have been reduced by 27–73 $bUSD_{2004}$ per year, of which 6–25 $bUSD_{2004}$ is attributable to motor vehicle use.

The subsidies for nuclear power are even more elusive to pinpoint in the publicly available literature. In IEA statistics, cumulative public energy R&D spending on nuclear constitutes 48%, or 211b€ (274 bUSD), and renewables 11%, or 50 b€ (66 bUSD), of the total 443 b€ (576 bUSD) R&D spending in OECD countries over the time period 1974 – 2014 [60]. According to a FS-UNEP study [61], global energy R &D expenditure on renewables totaled 9.1 bUSD (7 b€) in 2015, with corporate funding amounting to 4.7 bUSD (3.6 b€). Solar energy alone attracted 4.5 bUSD (3.5 b€), of which 2.6 bUSD (2 b€) was corporate investments. The private sector has been responsible for the majority of cumulative R&D investments in solar PV over the recent decades, and the sum of this contribution is only 2% of historic, mostly public, R&D money spent on nuclear energy [62]. Despite this fact, solar PV has been able to achieve a lower LCOE than nuclear power. Further, no nuclear power plant could be built if owners had to pay for the full cost of liability insurance [63]. However, this indirect subsidy is difficult to comparably quantify, since there is no payment unless a catastrophe occurs. Neglecting the NELD of a nuclear meltdown, this could be compared to a loan guarantee given for accruing a PV manufacturing facility, which would have to be paid only if the fabricator failed to repay its lenders. However, given that PV systems show accelerating diffusion and have demonstrated a very stable learning rate, the guarantee given to a PV manufacturer instead of to a nuclear power plant shows much less risks and better long-term profitability for a government [62,63]. In most European countries, operators need to cover only 700 M€ (910 bUSD) of damages (with the government covering an equal share), and in the US, the Price-Anderson Nuclear Industries Indemnity Act covers up to 13 bUSD (10 b€) for a single accident [64]. However, after the Fukushima accident, the Court of Audit has reevaluated the risks of nuclear reactors in France. Consequently, the future liabilities for new reactors could add 15 €/MWh (19.5 USD/MWh) to the levelised cost of electricity if operator liability is capped around 100 b€ (130 bUSD) [64].

Even excluding the liability costs, nuclear technology does not compare well financially with alternative energy sources (and especially poorly considering future prospects), with the LCOE of Hinkley Point C estimated at 113 €/MWh [53]. The opportunity cost of nuclear power is raised by a risk of a terrorist attack, and the subsequent immediate deaths and carbon emissions due to burning of buildings and infrastructure. The opportunity cost of nuclear power is further increased by the longer commissioning delays experienced by nuclear technology compared to alternative technologies [65]. Thus, the main restrictions on nuclear power are unresolved problems of long-term waste disposal, the risk of catastrophic accidents and associated liabilities, possible proliferation of weapons-grade fissile material and the failure of the technology to provide significant generation capacity

regardless of highest levels of governmental support [29]. Finally, institutions have proposed global nuclear phase-out scenarios in their sustainable energy studies [21,29,36,49,66], advocating for a major risk aversion and consideration of future generations, who would otherwise have to bear the responsibility of keeping an increased number of waste sites sealed off from the biosphere.

Now that important issues related to energy systems have been discussed in the context of a wider set of sustainability criteria, it is important to re-examine how influential energy scenario frameworks conform to or deviate from this proposed sustainability hierarchy. In essence, these scenarios were assessed on how a full range of sustainability considerations were taken into account. Upon such an examination, recommendations can be made regarding how such a hierarchy can be operationalised more completely in the future.

3. Methods

In total, eight studies, some with multiple scenarios, were selected as representative of global scenario modeling work based on their geographic scope. A wider range of studies was considered in related work [67], but the number was reduced to those that had a common representation of a global energy system scenario for 2050. A further criteria related to study selection included a perceived relevance and influence of the studies. In addition, each showed a specific goal being reached as well as a clear pathway towards it from the present time. The complete list of studies is:

- Royal Dutch Shell: Mountains & Oceans scenarios [68]
  Two scenarios provide storylines describing the pace of change, policy agenda and resource landscapes. The Mountains scenario presents a more centralized energy system based on fossil and nuclear fuels, with more advanced use of CCS. Alternatively, the more decentralized Oceans scenario has solar PV in the fore, with delayed employment of CCS. Thereby, it leads to higher emissions. The analysis extends to 2100.
- IEA: 2DS-hiRen variant [69] and WEO 450 [56]
  The IEA scenarios present unsustainable energy projections to trigger policy changes [56]. The IEA argues that the power sector should be accounted in any strategy which addresses economic growth, energy security, climate change and local air pollution [56]. Judging by the WEO contents, these are also modeling objectives in the scenario creation. Energy Technology Perspectives (ETP) provides the most advanced analysis of energy technologies in the IEA's modeling ecosystem. In the most recent studies, such as ETP 2015, an hourly resolved power sector is modeled. The main intervention scenario is the "2DS", a pathway compatible with limiting emission to keep the average global temperature increase to 2 °C. Three variant scenarios (no CCS, hiRen, hiNuc) were included in the 2010 and 2012 versions of the report. Each has been excluded from the latest editions of ETP as equal options.
  The IEA's flagship report, World Energy Outlook (WEO), includes a "450 scenario" (referring to CO_2 concentration of 450 ppm in the atmosphere), which describes a pathway consistent with the 2 °C target. The WEO modeling tool is less accurate in representing energy technologies than ETP modeling tools, and WEO is more conservative with respect to renewables. Overall, the IEA reports show pathways in which fossil fuels and nuclear power retain a strong role in future energy systems. For example, only 20% less fossil fuels are used in 2050 compared to 2009 in the 2DS (2012) scenario. For this reason, even IEA's intervention scenarios can be seen as reinforcing a status quo. Energy subsidies for renewables are described detail, and energy subsidy reform for fossil fuels is discussed [56].
- World Energy Council: Jazz & Symphony scenarios [70]
  The Jazz scenario is one in which incumbent fossil fuel industries dominate and corporations play strong roles in the global context. In opposition, Symphony shows a pathway whereby certain renewable energies are promoted and main actors are governments. Jazz is similar to Shell's Mountains scenario in that unconventional gas is highly utilized. By contrast, unconventional fuels are more expensive in the Symphony scenario, and stronger climate policies are established. WEC assumes that a "P2G breakthrough" can occur after 2035 in the Jazz scenario. This breakthrough occurs earlier in the Symphony scenario, enabling the integration of renewables into the energy system.
- IIASA: Gea efficiency, GEA Efficiency, Mix and Supply scenarios [29]
  The Global Energy Assessment (GEA) began as an attempt in 2005 by the founding Chair of the IPCC to realistically address climate change challenges. In doing so, a comprehensive, science-based analysis was needed to assess the global energy system [29]. In total, 60 possible transformation pathways were investigated, of which 41 satisfied Global Energy Assessment (GEA) goals. The main goals were: providing energy services to about 9 billion people in 2050 while maintaining an average growth of 2% global GDP, addressing this issues of access to modern energy services and clean cooking, enhancing energy security (reducing energy trade balances), containing the mean global temperature increase to less than 2 °C, reducing ambient air pollution (and thus adversary health impacts), and mitigating anthropogenic environmental pressure. Including both industrialized and developing nations, approximately 31% less energy per capita is used in the Efficiency scenario in 2050 compared to 2005. In contrast, the Supply scenario shows about 3% more energy per capita being used. The study acknowledges the unresolved challenges related to nuclear power and CCS. As such, the two technologies are not depicted as necessities to reach the set goals. The integrated assessment models employed provide a comprehensive macroeconomic view of the energy sector and its key uncertainties. At the same time, there is a less accurate representation of energy technologies.
- WBGU: Exemplary path [21]
  IPCC scenarios provide the basis of WBGU analyses. The 450 ppm target provides the basis of the Exemplary scenario, which is also built on the assumption of high economic and energy demand growth. In such a manner, investigating how sustainability goals could be reached without deep changes in consumption patterns was possible. Several sustainability guardrails outline the IPCC scenario: securing access to modern energy services, preventing air pollution, protecting land and marine ecosystems, using bioenergy is within special sustainability limits, and phasing out nuclear power. In the 2040 s CCS is introduced but phased out by 2100, and energy production is about 50% renewable by 2050.
- WWF: The Ecofys Energy Scenario [49]
- This scenarios shows a pathway in which 95% of final energy is provided by renewables by 2050. The transition is achieved by widespread electrification of demand sectors, use of renewable energy fuels particularly for transport and industry, rapid deployment of technologies, and aggressive end-use energy savings. About 31% efficiency gain is achieved in the Ecofys Energy Scenario compared to the baseline scenario in 2050, and includes both end-use efficiency improvements and electrification. Reduction of final energy demand is about 20% over the period 2010–2050. Bioenergy utilisation (about 180 EJ/yr in terms of primary energy) greatly surpasses what is regarded as sustainable by the WBGU and Greenpeace.
- Greenpeace: energy [r]evolution & Advanced energy [r]evolution [36]
- Greenpeace has several broad goals for its scenarios, including: phasing out of subsidies for fossil fuels and nuclear energy, internalising the social and environmental costs of energy, advocating stricter efficiency standards, setting out legally binding RE targets, reforming of electricity markets to favor renewable power generation, establishing cross-sectoral RE support schemes to exploit

synergies between the power, heating/cooling and transport sectors, providing stable returns and risk minimization for investors in RE, and increasing R&D budgets for RE and energy efficiency [36]. The Greenpeace scenarios achieve a widely or fully decarbonised energy system by 2050 while also regarding environmental policy targets. Greenpeace considers the implications of a fully renewable and sustainable energy system on supply and demand sides, investments, emissions and employment. The study includes a reference pathway from IEA, an energy [r]evolution scenario from 2012 whereby 83% of final energy is provided by renewables, and an Advanced energy [r]evolution scenario for 100% renewables by 2050. The Advanced scenario is characterized by higher mobility sector electrification, and renewable hydrogen is converted into synthetic hydrocarbons to replace remaining fossil fuels. About 3% average annual growth of global GDP is assumed over the period of 2012 – 2050, and the population is assumed to be 9.5 billion in 2050. Significant efficiency gains are achieved due to both fuel switching and improvements in end-use efficiencies. In the Advanced scenario about 47% less energy is used in 2050 compared to the reference scenario (in terms of both primary and final energy demand). In addition, final energy demand is reduced about 13% over the period of 2012–2050.

- Jacobson et al.: WWS [14,71]
- Roadmaps for 139 countries which show how the electricity, mobility, heating/cooling, industry and agriculture/forestry/fishing sectors can be powered mainly by wind, water and solar resources. Efficiency gains in total energy demand due to fuel switching and electrification are around 32% compared to a reference scenario, with an additional 7% reduction due to improvements in end-use efficiency. These gains match with assumed demand growth, which results in about the same amount of primary energy being used in 2050 compared to 2012. Other noted benefits of the WWS vision include reduced air pollution, mitigated global warming, positive net creation of jobs, stabilization of energy prices, reduced energy poverty and reduced risk of international conflicts over energy resources. To begin, only the US was modeled with high spatial and temporal resolution and with energy technologies accurately represented, whereas calculations for the rest of the world were based on average annual capacity factors.

A fuller description of each model can also be found from [67]. Each scenario was examined qualitatively with respect to how they adhered to the proposed hierarchy of sustainability established earlier. In addition, scenarios were examined quantitatively in terms of the energy generation and storage technologies that were employed in 2050.

A transparency checklist was created that analyzed the presence or absence of specific types of information (general, data presentation, assumptions, modeling properties). Personal judgement was used to determine if such information was presented, and if such presentation was adequate. Judgements were discussed and agreed upon by all authors of this work. Specific categories of transparency are presented with results in Table 3.

A sustainability checklist was created related to the exemplary sustainability guardrails previously discussed. To this end, several Yes/No questions were developed to determine how three scenarios adhered to such guardrails in relation to social, environmental and economic criteria. The full list of questions is presented with results in Table 4. For both the transparency and sustainability checklists, each item was personally judged by the authors as being i) explicity stated, ii) not fully disclosed, or iii) not available / cannot be determined.

4. Results

The energy generation and storage technologies included in the reviewed scenarios are set out in Table 1 and Table 2, respectively. The credibility of energy scenarios is assessed in Table 3. Results pertaining to the sustainability checklist are presented in Table 4. A full analysis and description of the scenarios can be found in [67]. Three scenario studies are selected for sustainability assessment, and the exemplary sustainability guardrails in Table 4 could be used as a checklist in the creation of an energy scenario. Table 1 shows the major differences between scenarios regarding conversion technologies utilized. In general, each scenario employs solar and wind energy although the table does not show the precise deployment of all different technologies (solar PV vs CSP, onshore vs. offshore wind). The table also shows the consistent use of hydro and geothermal power generation. At the same time, there are several notable differences. The WWS scenario is the only one which does not use bioenergy (biomass and waste) as a source of power. Furthermore, five scenarios do not employ nulcear power. Three of these same scenarios also do not show the use of fossil fuels or CCS technology. Of note is that all scenarios but one [21] which show nuclear capacity also show the need for CCS.

Table 2 shows the major differences between scenarios regarding storage technologies utilized. PtG storage technology is employed in all but the IEA 450 scenario. Battery technology is employed in all scenarios, but the importance of V2G connections is mixed (4 out of 9 scenarios). There is a tendency to employ both CAES (5 out of 9 scenarios) and PHS (6 out of 9 scenarios), and almost ubiquitous use of TES (8 out of 9 scenarios). In general, scenarios that name the widest ranges of storage technologies tend to add other storage options, such as flywheels and different types of capacitors. Importantly, no single scenario has quantified the demand for storage capacities on a global level [72].

Table 3 shows the results related to a transparency check on the studied scenarios. What is most evident is that the scenarios under review did not equally report what is seen as critical background information. Such information is generally used to ensure replicability of results, and opens the scenario to further scrutiny. The Global Energy Assessment of IIASA [29] scores highest in the transparency checklist, while the New Lens Scenario of Shell [68] and the World Energy Scenarios of WEC [70] score lowest. The IEA scenarios under study are generally transparent, but more full disclosure is lacking at times in key areas such as general information, access to data, and full disclosure of cost assumptions. More than half of the scenarios under review did not fully disclose cost assumption. The area in which most scenarios performed weakest was related to how they did not fully show how there may have been variance in assumptions.

Results of the sustainability checklist are seen in Table 4. In general, The Global Energy Assessment satisfied the widest range of sustainability criteria., whereas the IEA and Greenpeace studies focussed narrowly on CO_2 emissions and mitigating climate change. In those scenarios, several important environmental criteria were not addressed in the analyses, and the same was observed for several social criteria. Economic criteria were handled adequately in each scenario, but fuller disclosure is needed.

5. Discussion

It has been argued that the Paris agreement of COP21 is “a historical achievement and a genuine triumph of reasoning”, and that it is now time to implement action [51]. At the same time, much of the policy needed to begin climate action is underpinned by energy system modeling, some of which is not readily transparent [75]. Therefore, the need for openess, fairness, accuracy, and constructive criticism of energy system scenario design has never been greater in order to “avoid the looming humanitarian tragedy” [51]. At the heart of future energy scenario design are the roles played by various energy resources, conversion technologies and storage systems. However, the prominence of these roles varies greatly in each of the scenarios under investigation. For these reasons, sustainability guardrails beyond the scope of CO_2 emissions has been employed in order to safeguard critical planetary boundaries.

Comparison of included energy technologies (Table 1, Fig. 3) shows the diversity of thought on the relevance of each in future energy

Table 1
Power generation technologies included in the scenarios. Adapted from [67].

Deployed power generation technologies	Scenario													
	Royal Dutch Shell [68]		IEA		WEC [70]		IIASA [29]			WBGU [21]	WWF [49]	Greenpeace [36]		Jacobson et al. [14]
	Mountains	Oceans	2DS hiRen [69]	450 [56]	Jazz	Sym-phony	Effi-ciency	Mix	Supply	Exemplary	The Ecofys Scenario	Energy [r] evolution	Advanced energy [r] evolution	WWS
Solar	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Wind	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Hydro	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Bioenergy	X	X	X	X	X	X	X	X	X	X	X	X	X	
Geothermal	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Ocean			X	X						X	X	X	X	X
Nuclear	X	X	X	X	X	X	X	X	X					
Coal	X	X	X	X	X	X	X	X	X	X		X		
Gas (fossil)	X	X	X	X	X	X	X	X	X	X		X		
Oil	X	X	X	X	X	X	X	X	X	X		X		
CCS, after	~2020	~2040	~2020	~2020	~2035	~2030	~2040	~2030	~2025	2040				

scenarios. Firstly, it can be seen that the WWS scenario [14] is a clear outlier in the group since it excludes bioenergy altogether. However, it remains unclear as to why the previously identified potential (80–100 EJ/a) of sustainable biomass and waste cannot be utilized as energy resources, especially in light of vibrant forest and agriculture industries worldwide. Secondly, the role of CCS in future energy scenarios is not universally accepted. WBGU [21] assumes fossil CCS is introduced in the 2040 s and phased out by 2100. Interestingly, IIASA [29] claims that CCS and nuclear power are technological options, not necessities. IEA [48] does not justify or explain its value choice of having both nuclear and CCS capacity ramp-ups. Notably, IEA had three variant scenarios (no CCS, hiRen and hiNuc) in the Energy Technology Perspective report in the 2012 version [76], but has subsequently excluded them from the latest editions as equal options. However, the overall sustainability of CCS has been questioned (Section 2.1.4). These identified criteria are in line with Schellnhuber et al. [51], who claim there are three main reasons to reject “massive CO_2 removal or negative emissions”. For one, carbon pricing will induce a prohibitively high cost and risk for investors in fossil fuels. For another, a global divestment campaign away from fossil fuels has already begun which may “demand leaving most of the fossil fuel resources in the ground”. And the third reason is that the rapidly growing share of installed capacities of renewables will quickly force an implosion of the traditional, fossil fuel business paradigm. The reality of the rapidly increasing installed global capacities of solar PV and wind energy, combined with their rapidly decreasing costs, has not accurately been taken into account in energy scenarios featuring CCS and nuclear power. The same can be stated for battery storage, which is currently following a similar trajectory as solar PV and wind costs, and is equally described as too costly in the same scenarios.

The deployed energy storage technologies can be seen in Table 2. However, it proves that although energy storage technologies are discussed in the scenarios, the required capacities are not quantified. This result is in line with the findings of Koskinen and Breyer [72], who showed that global energy scenarios primarily assess storage demand qualitatively. Energy models should be able to quantify all technologies and their related costs. In addition, the dynamics and synergies of energy storage in different sectors of the energy system (power, heat, mobility) should be made evident, as is increasingly being done with continental and transcontinental energy system modeling [72]. It is insufficient to describe future energy storage with adjectives. Numbers must be used. In doing so on a global level, modellers can then estimate future costs of such technologies with greater accuracy. It follows that even the near to fully renewable scenarios with global scopes have not captured in detail how exactly the energy system would work on an hour-to-hour basis. This reveals substantial methodological shortcomings of all models used for the investigated scenarios, which also leads to a major questioning of how feasible the results of the investigated energy scenarios are at all, since a major future source of flexibility is missing in the analytical models. First insights from global analysis with hourly temporal resolution, based on real weather data and minimization of total system costs imply that global energy demand can be met in a cost-competitive manner entirely based on renewable energy technologies [14–17].

Next, Table 3 shows an assessment of transparency in the scenarios. Some of the boxes in the “General information” category are deemed yellow because it is judged they can be implicitly reasoned, although the best practice would be an explicit disclosure. A green color is given if the information is made available at least in supplementary materials online, to which there is a clear guidance in the main report. For example, the funding of the Solutions project (WWS scenario) is disclosed on the website of the project, and a great deal of supplementary materials to the scenario are also available online. Technically, WEC discloses references; however, as some of them are plain “WEC 2013”, it is not possible to go to the alleged original source of information. Another stripe of yellow in the “Data” category is deemed for some scenarios, as no clear distinction is made whether presented values are output from the model or hand set (exogenous) values. The best practice of this is provided by IIASA [29], which explicitly states model inputs and outputs, and WBGU [21], which describes the climate scenario first without WBGU's own input, and then explains the modifications due to applying self-determined sustainability guardrails. However, WBGU does not provide cost assumptions, considers only one scenario fulfilling sustainability targets, and describes model properties only briefly. For scenario transparency, the best practice is set by IIASA GEA. For example, the costs are provided online with clear indication in the report, and several variant scenarios are assessed: no-nuclear, no-CCS, and level of mobility electrification varied to investigate the technical feasibility of climate targets via alternative pathways. The best practice of defining and achieving comprehensive sustainability targets is set by the visionary report by WBGU, around ten years before the other studies assessed.

The results from sustainability assessment (Table 4) highlight the absence of comprehensive sustainability targets in scenario studies, a finding which is in line with the review of environmental studies in the Global Environmental Outlook 5 (GEO 5): “Generally, the scenarios explore a wide range of possible outcomes but, importantly and by design, almost none involves meeting sustainability targets – or sets them out as objective” [77]. Based on the performed analysis, it is a clear outcome that global energy scenarios lack assessment of planetary boundaries, basic human needs and welfare, and economic prosperity, or genuine progress, as a goal instead of continued growth as measured

Table 2
Energy storage technologies and time resolution of the modeling in the assessed scenarios. H_2 = hydrogen, PtG = power-to-gas, CAES = compressed air energy storage, PHS = pumped hydro storage, TES = thermal energy storage, V2G = vehicle-to-grid. Adapted from [67].

Deployed storage technologies	Scenario													
	Royal Dutch Shell [68]		IEA		WEC [70]		IIASA [29]			WBGU [21]	WWF [49]	Greenpeace [36]		Jacobson et al. [14]
	Mountains	Oceans	2DS hiRen [69]	450 [56]	Jazz	Symphony	Efficiency	Mix	Supply	Exemplary	The Ecofys Scenario	Energy [r] evolution	Advanced energy	WWS
H_2/ PtG (renewable)	X		X		X		X			X	X	X		X
Batteries	X		X	X	X		X			X	X	X		X
V2G			X				X					X		X
CAES			X				X			X	X	X		
PHS			X	X			X			X	X	X		X
TES	X		X	X			X			X	X	X		X
Other, specified	fossil fuels, hydrogen		flywheels, super capacitators				ultra-capacitators			capacitors, flywheels		flywheels		no stationary batteries
Time-step	NA		Yearly[b]	Yearly – 5 years[d]	About 12 h, seasonal		5 years			5 years	Yearly	Hourly[e]		Yearly[f]
Total period	1960–2060[a]		2010–2050[c]	1990–2040	2010–2050		2000–2050[a]			2000–2100	2000–2050	2012–2050		2012–2050

[a] Some of the results extend to 2100.
[b] In the 2015 edition, an hourly linear dispatch model has been added to analyze the power sector.
[c] Some results provided up to 2075.
[d] . Power generation curves based on hourly data, according to shown results in WEO 2015.
[e] Representative weeks for the total year.
[f] Six year period with 30 s time-step analyzed only for the US.

Table 3
Transparency checklist for creating credible energy scenarios. Green: Explicitly stated, yellow: not fully disclosed, red: not available/ cannot be determined. Adapted from [67].

	Scenario								
Information accessibility (at least accessible through the main report; e.g. web link provided)	Royal Dutch Shell [68]	IEA [56]		WEC [70]	IIASA [29]	WBGU [21]	WWF [49]	Greenpeace [36]	Jacobson et al. [14]
	New Lens Scenarios	ETP (2DS)	WEO (450)	World Energy Scenarios	Global Energy Assessment	Exemplary	The Energy Report	energy [r]evolution	WWS
General information									
Author/ collaborators	Red	Green	Green	Green	Green	Green	Green	Green	Green
Ordered by whom	Yellow	Yellow	Yellow	Red	Green	Green	Green	Green	Yellow
Funding acknowledged	Yellow	Yellow	Yellow	Red	Green	Green	Green	Green	Green
Purpose of study	Green	Green	Green	Green	Green	Green	Green	Green	Green
Data									
References can be traced back to original sources	Red	Green	Green	Yellow	Green	Green	Green	Green	Green
Clear distinction of assumed, processed and modelled values	Red	Yellow	Yellow	Red	Green	Green	Yellow	Yellow	Yellow
Assumptions									
Scenario frame explicitly defined	Green	Green	Green	Green	Green	Green	Green	Green	Green
Disclosure of costs	Red	Yellow	Yellow	Red	Green	Red	Yellow	Green	Green
Climate/policy constraints considered	Yellow	Green	Green	Yellow	Green	Green	Green	Green	Green
Variants to main scenarios considered	Red	Green	Red	Yellow	Green	Yellow	Red	Red	Red
Modelling									
Documentation traceable	Red	Red	Green	Green	Green	Green	Red	Green	Green
Model properties described	Red	Green	Green	Green	Green	Yellow	Green	Green	Green

conventionally as units of GDP. However, more appropriate indicators of progress have been developed, such as Human Development Index, Happy Planet index, Indicators of Sustainable Development (United Nations), Environmental Performance Index/Environmental Sustainability Index, Genuine Progress Indicator, and Green GDP [78].

The results of this work suggest that a greater diversity of sustainability criteria be used as guardrails in future energy scenario design. Such guardrails can be used more effectively to reduce risks for the future related to climate change. In addition, having a focus on more than just CO_2 emission mitigation would decrease the vulnerability of the system related to the broader spheres of sustainability, thereby resulting in greater overall system resilience. This observation is in line with O'Brien et al. [20], who conclude that because of the complexity of energy systems, major issue such as climate change cannot be analyzed on a single level. They argue that environmental problems must be addressed clearly in a social context. The study also advocates adherence to sustainability criteria that are hierarchical, but emphasise a need to view the hierarchy in more dynamic terms. Accordingly, they propose embracing the concept of a so-called "panarchy", within which "arrangements that include a wider group of stakeholders interacting across different levels, perhaps drawing on principles of coalition building or deliberate democracy, may better address the dynamics and complexities of climate change".

O'Brien et al. claim that there is a danger that new environmental contracts based only on CO_2 mitigation will serve to reinforce the power and economic structures that are the root cause of increased CO_2 emissions and climate change. Further, a purely environmental contract or solution that excludes social, economic and political factors would be "unlikely to change anything". For these reasons they argue that a more diverse, socio-ecological contract is preferred, one which must consider "debts to the past as well as obligations to future citizens". This idea is echoed by Folke [19], who states that the current socio-ecological system is vulnerable due to the fact that has lost resilience, which in turn has caused a lack of adaptability. They also highlight that through analyses of problems and solution on broader spatial and temporal scales, the panarchy, resilience can be recaptured. Likewise, Molyneaux et al. [79] reaffirm the idea that a broader size and scope of energy systems must be understood in order to ensure the resilience that enhances overall economic stability.

Sharifi and Yamagata [80] offer a complex conceptual framework upon which to analyze urban energy systems. This framework is also comprised of intertwined components and dimensions of sustainability which ultimately aim to ensure availability, accessibility, affordability, and acceptability of energy systems. They introduce an exhaustive list of principles that contribute to the abilities needed to ensure energy system sustainability and resilience. Upon developing 196 planning and design criteria for urban energy systems, the study divides them into five major themes: infrastructure; resources; land use, urban geometry and morphology; governance; and socio-demographic aspects and human behaviour. The authors caution that energy systems function across several scales (micro, meso, macro) and that these scales "cannot be disentangled".

Importantly, Sharifi and Yamagata [80] suggest that their broad conceptual framework and criteria can be used as an assessment tool. One of the purposes of such a tool is "to provide guidelines for future developments that can be communicated to citizens, planners, and policy makers". In this manner, the sustainability hierarchical proposed in this current work can serve as an assessment tool for energy system modellers during future energy scenario design and a more general audience who are influenced by global energy system scenario reports and publications. In the end, a more broadly informed society can engage in a more meaningful discourse on the future of energy globally.

The intention of this research was to provide a systematic review of previously published global energy scenarios in order to advance the field of energy scenario modeling. A new framework and sustainability checklist are proposed from a mix of new perspectives that are intended

Table 4
Sustainability checklist for global energy scenarios. Green: Explicitly stated, yellow: not fully disclosed, red: not mentioned. Adapted from [67].

Studies	IIASA GEA [29]		IEA WEO [56]		Greenpeace A sustainable world energy outlook [36]	
Indicators: Is there a scenario included, in which …	Yes/No	Page	Yes/No	Page	Yes/No	Page
Environmental						
a 2°C compatible pathway is presented?	Yes	1217, 1259	Yes[1]	55	Yes	
stress relief on phosphorus and nitrogen cycles is considered?	Yes/No[2]	39, 240	No[3]	481	No	
mitigation of biodiversity's rate of loss is assessed?	Yes/No[2]	240	No[4]	437	Yes[5]	223
land system change is limited (and restricted biomass for energy included)?	Yes[6]	241	No		Yes[5]	223-225
stress on freshwater use is assessed?	Yes[7]	242, 1506	Yes/No[8]	257, 338	No	
reduction of chemical pollution is assessed?	Yes/No[9]	241	No		No	
alleviation of stratospheric ozone depletion is considered?	Yes/No[2]	240	No		No	
mitigation of atmospheric aerosol loading is assessed?	Yes/No[2]	240	No		No	
mitigation of ocean acidification is assessed?	Yes/No[2]	240	No		No[10]	19
Social						
universal access to modern energy services by 2030 is considered?	Yes	1217, 1260, 1264	No[11]	107	No[12]	32
improved human health perspectives are assessed?	Yes	241, 1217, 1259	Yes/No[13]	300, 567	No	
a "nuclear phase-out" is considered?	Yes	1234, 1243	No		Yes	59
a "fossil fuel phase-out" is discussed?	Yes[14]	1284	No		Yes	59
an "energy democracy[15]" is considered?	No		No		Yes/No[16]	34
Economic						
The rate of efficiency improvements is speeded up?	Yes	1223, 1241	Yes/No[17]	396	Yes	270
diversification of primary energy mix is assessed?	Yes[18]	352, 1230	Yes/No[19]	348, 554	No	
a phase-out of pervasive energy subsidies[20] (direct incentives, breaks/credits, health/military sector expenditures, cost of emissions) is assessed?	Yes[21]	26, 42, 66	Yes/No[22]	27	Yes/No[23]	34

1. The 450 scenario represents a pathway compatible with limiting global warming to 2 °C above the preindustrial era within the century; however, this plays a minor role in the report, which mostly builds on the"New Policies Scenario". The 450 scenario is discussed in a separate report [48].
2. Boundaries acknowledged; energy scenario compatibility not explicitly assessed (i.e. boundaries are not endogenous to the used models).
3. In the special assessment for India, over-consumption of nitrogen and phosphorus in fertilizers is acknowledged.
4. In the special assessment for India, biodiversity loss in the case of using traditional biomass is acknowledged.
5. Greenpeace applies strict sustainability criteria for biomass to ensure that biodiversity is enhanced and conflicts do not take place.
6. Less than 15% global land cover converted to cropland. Limited bioenergy potential: 80 EJ/year in primary energy in 2050, 125 EJ/year in 2100.
7. Global sustainable freshwater withdrawal is estimated to be in theto be in the range of 5000 – 9000 km^3/year (4000 – 6000 km^3/year for consumptive use). Current withdrawal estimated at 4000 km^3/year, of which about 3000 km^3/year is consumptive.
8. Only coal power related freshwater consumption is assessed. Conflicts related to unconventional gas production and freshwater supply preservation acknowledged but boundaries not assessed.
9. Pollutants contributing to human health and ecosystem damage reduced by 2030 and eliminated by 2050; no boundaries proposed or assessed.
10. Ocean acidification is acknowledged; planetary boundaries are not promoted or proposed.
11. Access to both electricity and clean cooking improve; however, universal access to modern energy services by 2030 is not investigated.
12. Universal access to modern energy services is promoted, but not assessed in the scenarios.
13. It seems reduction of local air pollution is an objective in the IEA modeling; however, boundaries are not presented for the global analysis.
14. Fossil oil accounts for 9 – 15% of global primary energy in GEA pathways in 2050, and less than 1% by the end of the century.
15. Here energy democracy means that the scenario's energy mix is made according to a public consultation; either existing question polls are used or stakeholders are included in the creation process of the scenario study.
16. However, one of the key elements proposed by Greenpeace is that [renewable] energy support schemes have a public acceptance/ support.
17. The IEA scenarios do not investigate a high electrification case in which primary energy consumption could be reduced by minimizing the share of thermal generators and internal combustion.
18. The Shannon-Weiner Diversity Index [73] is mentioned as an example for assessing resilience of electricity generation. The"Mix"-scenario represents diversified energy portfolios.
19. In the special assessment for India, diversification of primary energy mix, imported fuels and power generation are assessed. It is unclear whether diversification is an objective as such in IEA's modeling.
20. Although studies usually call for the phase-out of energy subsidies, they are not usually defined or quantified in the scenarios. If such assessments, as done by IMF authors [57], were to be quantified, the intervention scenarios would likely show economic net benefits instead of costs. For a "missed benefits assessment" of global energy system, see [74].
21. Phase-out of fossil fuel subsidies and benefits in air quality are quantified. However, more recent estimations suggest that health costs are underestimated in GEA [57].
22. Phase-out of remaining end-user subsidies by 2030 called for in special report Energy and Climate Change [48].
23. Phase-out of all fossil fuel subsidies is called for; however, these subsidies are not defined or assessed in the report.

to guide the creation of new, future energy scenarios by modellers. This novel checklist has been applied to three scenarios in an exemplary manner. However, it is left up to future researchers to decide exactly how to implement the recommendations in their own work. In addition, while it is beyond the scope of this work to state the full impacts of the application of the proposed guardrails, it must be acknowledged that these impacts would be significant. In essence, new sustainability goals are proposed, but it is left to future modellers to both test and find the most feasible methods of achieving them. Future scenarios should especially show the economic impacts of implementing stricter

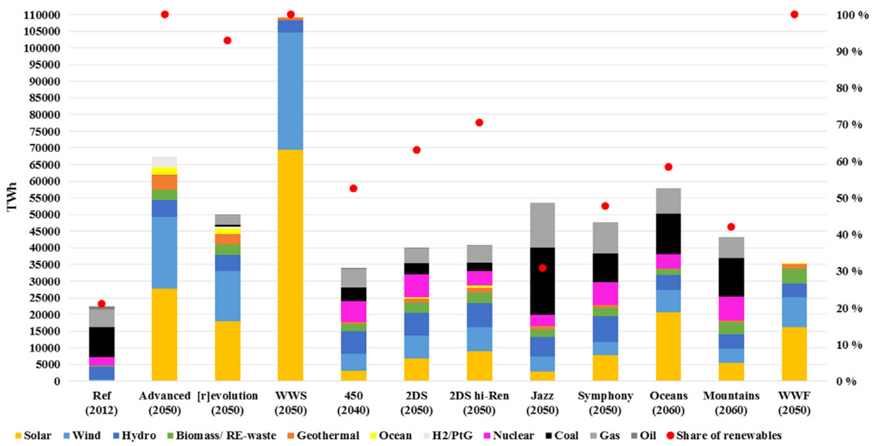

Fig. 3. Electricity generation (TWh) from different sources and share of renewable power in total generation (%) in the assessed scenarios. The reference generation for the year 2012 is based on Teske et al. [36]. For WWF and Shell scenarios the values are for final consumption, for WWS electricity generation is estimated from supplementary materials [71], and for the rest the values are for generated electricity. Adapted from [67].

sustainability criteria against alternative scenarios in a transparent manner. Part of this transparency will be acknowledging a fuller range of costs and benefits, and whether they are estimated, assumed, or real.

Future scenarios should also endeavour to show the technological challenges that may be associated with achieving greater sustainability. Moreover, adhering to the proposed sustainability guardrails may have a high relevance to future grid planning. For example, there are many ways to achieve universal access to modern energy services. In some parts of the world, this could best be achieved by expansion of high voltage grids. In others, it might be better to promote off-grid solutions or mini-grids. The challenge for scenario modellers will be to show that there may be several pathways towards sustainability, and that some may be more feasible than others in a given context. The ultimate goal of scenario modellers should always be to reduce uncertainty about the future, and to expand meaningful scientific and public discourse on the transition towards greater sustainability in global energy systems.

6. Conclusions

Visions of how to quantify sustainability targets in real world decision making are needed to start meaningful discussions about the futures we want, and to pave the way for informed actions. For this purpose, incorporating the planetary boundaries framework into national and global decision-making is a promising and active area of present and future research. Transparency and credibility of energy scenarios can be generally improved by:

- better disclosure and clear referencing of used sources of information,
- indicating how data are processed,
- providing a full set of cost assumptions,
- exploring how variations in cost assumptions influence the outcomes of the study,
- setting objectives on sustainability targets and measuring the results in that dimension,
- discussing the impact of the scenario results on given planetary boundaries,
- implementing adequate methodology for analytically describing the major flexibility characteristics of energy systems with high shares of renewables, such as storage capacities, function of grids, demand response, resource complementarity, supply side management and energy sector coupling
- disclosure of who has ordered the study by clarifying sources of funding.

Especially, low-cost PV combined with low-cost storage is to be investigated in future research. How to operationalize environmental, socio-economic and ethical dimensions in national and international decision-making is the challenge future research needs to answer as well. Given the quantifiable, safe operation limits of Earth systems, social conventions, such as contemporary market rules, laws, taxes, subsidies and political targets should contribute to limiting human actions to within the planetary boundaries.

Energy system models should show how scenarios achieve sustainability in a broader sense. This should not be an unmanageable burden if the hierarchical framework proposed in this work is observed during scenario design. Importantly, policymakers should now have a more complete framework upon which to judge the quality of various energy system scenarios beyond the current focus on CO_2 emissions. Indeed, it should also be possible to see past possible vested interests that too often are present in the modeling of future energy system scenarios. For government officials and lawmakers, if a more broad and comprehensive criteria of sustainability is adhered to throughout the process of policymaking, it should not only be possible to achieve goals related to climate change mitigation, but also create a more resilient energy system. This would fulfill a valid social contract with the future generations, who will also be the beneficiaries of such a long-lived socio-technical system.

According to this analysis, fully renewable energy system scenarios fulfill a set of environmental, socio-economic, and ethical sustainability objectives in the most comprehensive manner. For this reason, fully renewable energy system scenarios should thus be regarded as real policy options and set as references for alternative options.

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